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Threshold Effects between Ecosystem Services and Natural and Social Drivers in Karst Landscapes

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Abstract: It has been shown that there are thresholds of influence on the response of ecosystem services to their drivers, and the range of drivers that provide high levels of ecosystem services can be delineated through thresholds. However, due to the spatial heterogeneity of landscapes in karst regions, the results of ecosystem service threshold studies in non-karst regions may not be applicable to karst regions. This study explores the threshold effects between ecosystem services in karst landscapes and their natural and social drivers. It is shown that there are nonlinear constraints between them, and different critical thresholds exist for different kinds of ecosystem services. The main thresholds for water supply services include the slope (43.64°) and relief amplitude (331.60 m); for water purification services, they include relief amplitude (147.05 m) and distance to urban land (DTUL) (32.30 km); for soil conservation services, they include the normalized difference vegetation index (NDVI) (0.80) and nighttime light intensity (43.58 nW·cm^{-2}·sr^{-1}); the main thresholds for biodiversity maintenance services include population density (1481.06 person·km^{-2}) and distance to urban land (DTUL) (32.80 km). This enables regional ecological conservation planning based on different threshold ranges corresponding to different ecosystem services to meet the different needs of different decision makers.

Keywords: ecosystem services; threshold effects; karst; natural and social drivers

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1. Introduction

Ecosystems provide multiple ecosystem services (ESs) to society [1], including provisioning services, regulating services, supporting services, and cultural services; the ecosystem service value (ESV) assigns a monetary value to ecosystems and their key ecosystem goods and services [2]. Nature-based solutions (NBS) are key to achieving regional sustainable development, and ecosystem services are a crucial concept within current nature-based solutions [3,4], which contribute to support sustainable and resilient urban planning [5]. The substantial contributions of ecosystem services to sustainable well-being should be at the core of the fundamental change needed if we are to achieve a societal transformation to a sustainable and desirable future, there is a need in integrating ecosystem services and natural capital into mainstream policy [6], and help planners and decision makers at all levels to make the value of nature an integrated and 'natural' element to consider, equating it with human well-being [7].

The ecosystem service concept is an important integrated framework in sustainability science [8], as a bridge between natural and social ecosystems [9], ecosystem services are important for maintaining the ecological balance of cities and promoting the sustainable development of urban areas [10]. Mapping and assessment of ecosystems and their services (MAES) is recognized as a crucial step toward sustainable policies and decisions that promote human well-being and preserve life-sustaining ecosystems; it can be integrated into the design of future policies with a direct impact on ES and biodiversity conservation, thereby enhancing sustainable management of natural capital at national and sub-national levels [11]. And the research on estimating the future value of ecosystem services in global scenarios also made the connection clearer between future human well-being and the well-being of the rest of nature in quantitative terms [12].

Ecosystem services are more influenced by external environmental factors than by interactions among themselves in general. Previous studies have achieved certain results on the main factors affecting ecosystem services in different regions. A study on Central Asia has analyzed the effects of land use/land cover (LULC) and climate change on three ecosystem services, namely, net primary productivity (NPP), water yield, and soil retention, and has shown that LULC has a greater effect on NPP, while climate change has a greater effect on water yield and soil retention [13]. A study on the China–Mongolia–Russia Economic Corridor analyzed the main drivers affecting five ecosystem services (water yield, soil retention, carbon storage, habitat quality, and food production) and showed that normalized vegetation index, population density, and precipitation had a major impact on ecosystem services [14]. A study on the Wujiang River Basin in China's karst region analyzed the dominant drivers of six ecosystem services (water yield, soil conservation, net primary productivity, habitat quality, recreation services, and food production). The results showed that precipitation is the main driver influencing the trade-off between water production and food production, and normalized vegetation index is the dominant factor influencing the trade-off between food production and net primary productivity [15]. Understanding the factors affecting multiple ecosystem services could help us better manage ecosystems [16].

However, under various direct or indirect influences of both natural and social factors, ecosystem structure and function undergo nonlinear changes, which greatly alter ecosystem functions and services [17], and many ecosystem services, such as support and regulation services, are declining, so the incorporation of ecological thresholds in environmental management is essential [18]. Therefore, exploring the thresholds of influence between ecosystem services and natural and social factors is a current scientific issue of interest in the field of research on the relationship between ecosystem services and the role of drivers. A number of scholars have conducted research on the ecosystem services of different types of ecosystems and the thresholds between ecosystem service values and driving factors. A study on urban ecosystems revealed the key thresholds of ESV under the synergistic effects of multiple factors and that a certain threshold range exists for evapotranspiration, precipitation, the level of economic development, and landscape diversity, which can effectively contribute to an increase in the ESV [19]. A study on grassland ecosystems identified the constraints of drivers on ecosystem services, the significant seasonal changes in ecosystem service provision, and the threshold of vegetation cover for the inhibition of the wind erosion of soil [20]. A study on the Loess Plateau ecosystem analyzed the relationship among climate factors, ecosystem services, and the threshold effect. Among various climate factors to which ecosystem services responded, precipitation was the most important climatic factor, and when precipitation reached a certain threshold, it had a positive effect on net primary productivity and water yield [21]. A study on the Tibetan Plateau ecosystem assessed the impacts of changes in climate and vegetation cover on ecosystem services, and the effects of certain temperature and precipitation thresholds on ecosystem services were positive [22]. To summarize, existing studies show that there is a certain threshold effect between the ecosystem services provided by different types of ecosystems and a variety of environmental factors.

Due to the specific geological background and hydrological conditions, ecosystems in karst areas are characterized by ecological fragility with respect to external disturbances [23], and it is difficult to recover ecosystems in a short period of time if they are degraded. Under the influence of various natural and social environmental factors, the ecosystem services provided by karst ecosystems to human beings have become increasingly complex [24]. Current studies on karst ecosystem services have focused on the analysis of spatial and temporal changes in ecosystem services [25,26] and drivers [27,28], as well as on the analysis of synergistic ecosystem service trade-offs [29,30]. In contrast, there are fewer studies on thresholds for karst ecosystem services. Are there any nonlinear thresholds between ecosystem services and their drivers in karst areas as well? This study aims to explore the threshold effects between karst ecosystem services and natural and social factors. Firstly, four key ecosystem services in karst regions, namely, water supply, water purification, soil conservation, and biodiversity maintenance [31], were selected for quantification. Secondly, different ecosystem services were separately plotted with 12 typical natural and social drivers in a scatterplot. Then, constraint lines between different ecosystem services and drivers were constructed, and the threshold values were determined based on the constraint lines. Finally, the ranges of drivers with higher ecosystem service levels were analyzed through the threshold values.

2. Materials and Methods

2.1. Study Area

Guiyang City (106°07′ E–107°17′ E, 26°11′ N–26°55′ N) is located in the central part of Guizhou Province, China (Figure 1). It is the capital of Guizhou Province and one of the typical karstic mountainous cities in southwestern China [32], with an area of about 8043 km^2. Guiyang City has a plateau mid-hill landscape, and the altitude is 880–1659 m. The terrain is high in the southwest and low in the northeast, and most of the rivers flow from the southwest to the northeast, with a high degree of underground river development. Guiyang city is in the subtropical plateau monsoon humid climate zone [33], and it has a relatively mild climate. The average annual temperature is 15.3 °C, the average summer temperature in July and August is 23.2 °C, the average annual precipitation is 1129.5 mm, and the average annual relative humidity is 77% [34].

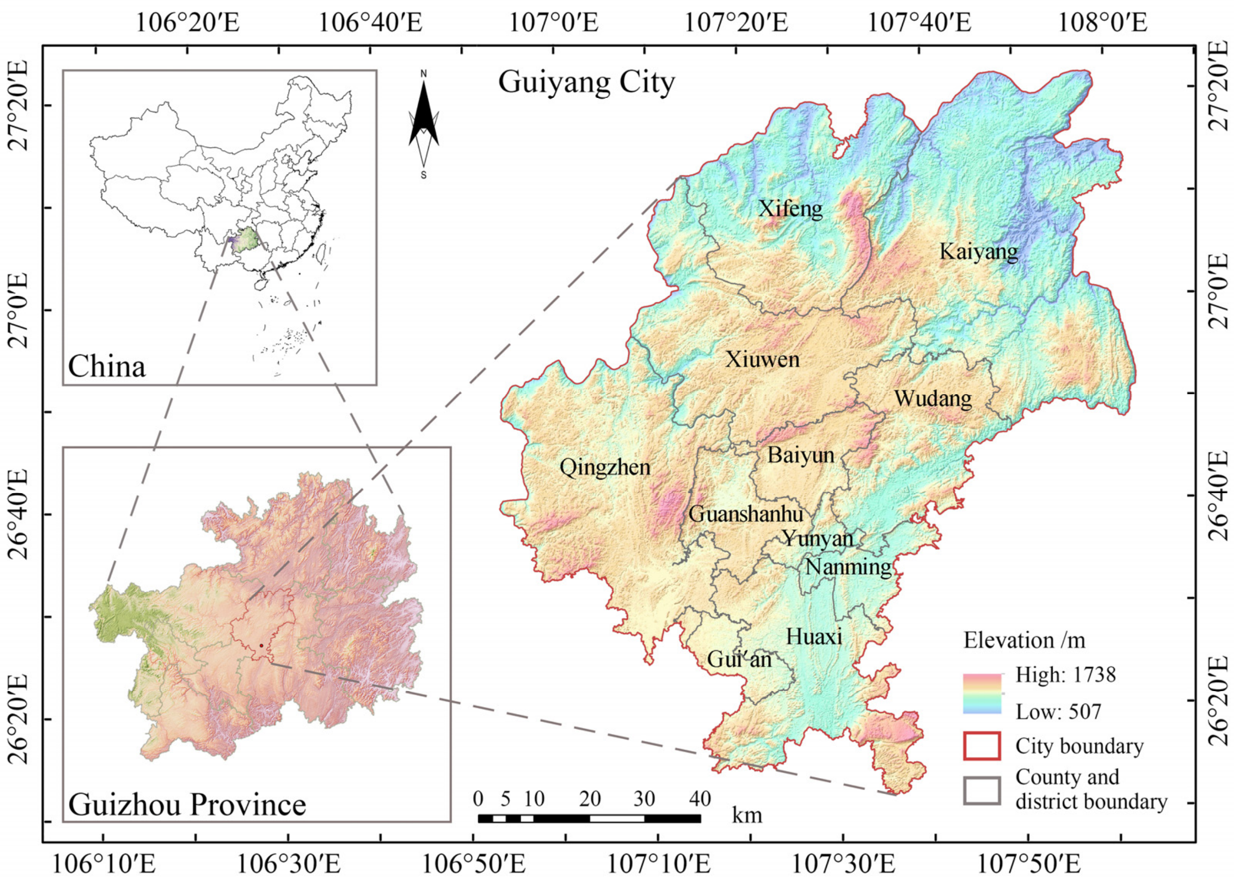


Figure 1. Map providing an overview of the study area.

The karst landforms in Guiyang City account for 71.8% of the total area. Karst is a type of landscape where the dissolution of the bedrock has created sinkholes, sinking streams, caves, springs, and other characteristic features. Clean groundwater can be found in healthy karst ecosystems with undisturbed soils and vegetation; at the same time, there is a great variety of habitats unlike those in non-karst landscapes, and they are often relatively isolated from their surroundings. Karst landscapes host great biodiversity in terms of animal and plant species, including rare and endemic species [35]. In addition, a large number of species temporarily and opportunistically utilize karst contexts as one of a variety of suitable habitats; this could affect the composition and richness of local vegetation and the associated fauna [36]. These provide valuable ecosystem services in natural water purification and biodiversity conservation. Therefore, emphasizing the provisioning of ecosystem services is essential in supporting the concept that karst regions are vital for human well-being because they host valuable resources and fundamental ecosystem processes [37]. Although China has responded to ecosystem degradation by investing heavily in protecting and restoring the natural environment since 2000 and ecosystem services have improved [38], the limitations of the geomorphological features of karst regions make the ecological environment in Guiyang City more fragile, the ecosystems more prone to degradation, and the relationships among ecosystem services complex, causing Guiyang City to be worthy of concern.

2.2. Data Sources

In this study, 12 drivers were selected to analyze the relationship between karst ecosystem services and their effects. The 12 factors included 6 natural factors and 6 social factors; these factors have already been shown in studies to be more closely related to ecosystem services, and they deserve further attention [39–42]. The following natural factors were selected: the normalized difference vegetation index (NDVI), mean annual temperature (Temperature) (°C), mean annual precipitation (Precipitation) (mm), elevation (m), slope (°), and relief amplitude (m); the following social factors were selected: population density (person·km^{-2}), nighttime light intensity (nW·cm^{-2}·sr^{-1}), distance to road (km), distance to water (km), distance to urban land (DTUL) (km), and distance to rural settlement (DTRS) (km). The specific information on the data used is shown in the following table (Table 1).

Table 1. Data overview and data sources.

Data Name	Data Spatial Resolution	Data Sources
China Multi-Period Land Use Remote Sensing Monitoring Dataset (CNLUCC)	1 km	Resource and Environment Science and Data Center, Chinese Academy of Sciences: https://www.resdc.cn/, accessed on 21 March 2023
China Soil Dataset (v1.1) based on the World Soil Database (HWSD)	1 km	National Cryosphere Desert Data Center: http://www.ncdc.ac.cn/portal/, accessed on 21 March 2023
China Bedrock Depth Map	100 m	Yan et al. (2020) [43]
China Month-by-Month Potential Evapotranspiration Dataset, 1901–2022	1 km	National Earth System Science Data Center: http://www.geodata.cn/, accessed on 21 March 2023
Normalized difference vegetation index data by year, 2000–2022	1 km	Didan et al. (2015) [44]
Monthly mean air temperature dataset for China (1901–2022)	1 km	National Tibetan Plateau Science Data Center: https://data.tpdc.ac.cn/home, accessed on 21 March 2023
Monthly precipitation data set for China (1901–2022)	1 km	National Tibetan Plateau Science Data Center: https://data.tpdc.ac.cn/home, accessed on 21 March 2023

Table 1. *Cont.*

Data Name	Data Spatial Resolution	Data Sources
ASTER GDEM Digital Elevation Data	30 m	Geospatial Data Cloud: http://gscloud.cn/, accessed on 21 March 2023
Gridded Population of the World (GPW), v4	1 km	Socioeconomic Data and Applications Center (SEDAC): https://sedac.ciesin.columbia.edu/, accessed on 21 March 2023
Global 2000–2022 NPP-VIIRS Nighttime Lighting Dataset	1 km	Chen et al. (2021) [45]
China Road Data	-	Open Street Map: https://www.openstreetmap.org, accessed on 21 March 2023
China Water System Data	-	Open Street Map: https://www.openstreetmap.org, accessed on 21 March 2023

2.3. *Quantification of Ecosystem Services*

Four key ecosystem services in karst landscapes were focused on in this study [31]: water supply (provisioning service), water purification (regulating service), soil conservation (supporting service), and biodiversity maintenance (supporting service). Since the quantification of cultural services is subjective, they were not included in this study to avoid uncertainty.

The InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs Tool) model [46] is an advanced tool for integrating natural capital as a basis for decision making. The tool is the result of The Nature Capital Project, jointly developed by Stanford University, the University of Minnesota, The Nature Conservancy (TNC), and the World Wide Fund for Nature (WWF) [47], which is aimed at governments, corporations, non-profit organizations, and multilateral development organizations, among others, and it provides services in the areas of land use planning, marine spatial planning, strategic environmental assessment, ecosystem service valuation, climate adaptation strategies, and mitigation and offset trading [48]. Since its release in 2007, the model has gained a wide range of international applications and has attracted the attention of scholars working in a variety of disciplines, including geography, ecology, and environmental science [49]. As a mature ecosystem service assessment model [50], the InVEST model has been widely used in many studies of ecosystem services in karst regions [51].

The InVEST model includes several analysis modules, ecosystem services in karst landscapes in this study were quantified using the corresponding modules in the InVEST model 3.12.1 [52]. Land use/land cover data are necessary for all modules. Water supply was quantified using the annual water yield module to calculate the water yield [53]. For the annual water yield module, precipitation, evapotranspiration, root restricting layer depth, and plant available water content were necessary. A biophysical table, watersheds, and sub-watersheds also needed to be added. The Z parameter option in the annual water yield module was filled with 1.5. Water purification was quantified using the nutrient delivery ratio module to calculate the nutrient retention [54]. For the nutrient delivery ratio module, a digital elevation model and nutrient runoff proxy were necessary, and watersheds and a biophysical table also needed to be added. The threshold flow accumulation and the Borselli K parameter options in the nutrient delivery ratio module were filled with 1000 and 2, respectively. Soil conservation was quantified using the sediment delivery ratio module to calculate the soil conservation capacity [55]. For the sediment delivery ratio module, erosivity and soil erodibility were necessary, and a biophysical table and watersheds also needed to be added. The threshold flow accumulation, Borselli K parameter, maximum SDR value, Borseli IC0 parameter, and maximum L value options in the sediment delivery ratio module were filled with 1000, 2, 0.8, 0.5, and 122, respectively. Biodiversity maintenance was quantified using the habitat quality module to calculate the habitat quality [56,57]. For the habitat quality module, a threat table and sensitivity table were necessary. The half-saturation constant option in the habitat quality module was filled with 0.05. The required data were input into the module for calculation after removing outliers and missing values. The service quantities of the four ecosystem services were calculated in 2000, 2005, 2010, 2015, and 2020. The spatial resolution of the quantified ecosystem service data was 1 km.

2.4. Constructing Constraint Lines Based on Ecosystem Service Scatter Cloud Maps

In complex ecological processes, the relationship between two variables may be affected by many other factors in addition to the interaction, and thus, the relationship between these two variables often presents a distributional characteristic that is similar to a scatter cloud. The constraint variable cannot completely control the change in the response variable but has a limiting effect on it, so the distribution of the response variable cannot exceed a certain range. At this point, the constraint line method was a better choice for characterizing the relationship between two variables, as a constraint line can characterize the range of the distribution of a response variable under the action of the limiting variable or the potential maximum value that can be reached [58,59]. In the research field of ecosystem services, a constraint line represents the potential range of responsive ecosystem services under the influence of constraint drivers [60].

In order to explore the patterns of change in the four ecosystem service thresholds, constraint lines were constructed based on the scatter cloud among the four ecosystem services and 12 drivers in this study [61]. Soil retention and population density were taken as their common logarithms for the study due to the large span of the data. The range of drivers on the x-axis in the scatter plot was averaged into 100 sections to obtain 100 columns. To minimize the effect of outliers, the 99.9% quantile in each column was chosen as the boundary point, resulting in approximately 100 boundary points for fitting each constraint line [62,63]. The 99.9% quantile values were completed with Microsoft Excel 2010 for the calculations [64,65].

2.5. Identifying Thresholds Based on Constraint Lines

There is a nonlinear relationship between ecosystem functioning and services [66–70], and there are often nonlinear effects between ecosystem services and their drivers [71,72]. Restricted cubic spline analysis is a common approach for variables that exhibit nonlinear relationships [73,74]. The restricted cubic spline (RCS) is essentially a continuous smooth segmented polynomial function that divides a continuous variable into segments and performs a segmented regression such that the continuous variable X exhibits a smooth curve over the entire range of values. The segmentation points are called nodes, and the number and location of the nodes determine the shape of the spline curve. In most cases, the position of the nodes has little effect on the RCS fit, and the number of nodes is a more critical parameter [75], as it determines the shape of the curve and the degree of smoothness. The node selection is generally from 3 to 7. Harrell (2017) [76] suggested that the model fits better when the number of nodes is 4, while the smoothness of the curve can be taken into account and the accuracy reduction caused by overfitting can be avoided. When the sample size is large, such as when the dependent variable is uncensored, continuous, and greater than 100, 5 nodes is a better choice. For small samples (e.g., $n < 30$), 3 nodes can be chosen.

In this study, RCS models fitting different numbers of nodes were separately compared, and the model with the best fit was selected for the study. The turning node locations of critical thresholds were identified based on the curve changes in the model, and the natural and social thresholds of different ecosystems were determined based on the locations of the drivers corresponding to the node locations. The RCS analysis was accomplished with the rms package in R 4.2.3 and R Studio 2022.12.0-353 [77].

2.6. Scope of Application and Uncertainty of the Study

The focus of this study is mainly on the urban karst area in Guiyang City, China. Given the complexity of the environmental context of karst regions and other terrestrial regions with less urbanization impacts that are more constrained by the special geological context of karst environments [78], the changes in ecosystem services are likely to be different from those in urban areas, and the role of the relationships between their drivers may also be more complex. Although it may not be able to cover all karst regions, the results of this study can provide a more effective reflection of the thresholds of influence between ecosystem services and their drivers in the karst mountainous urban region of southwest China represented by Guiyang City [79].

3. Results

3.1. Patterns of Spatial and Temporal Changes in Ecosystem Services

The distribution patterns of the four ecosystem services in Guiyang City varied widely in space (Figure 2). The water yield (Figure 2a) had the highest values in the western part of the city, high values in the eastern part, and low values in the southern part of the city. The water yield decreased from 2005 to 2010 and gradually increased from 2015 to 2020. Nutrient retention (Figure 2b) had high values that were more distributed in the periphery of the city, high values in the southwest, and low values in the central part of the city. From 2000 to 2020, nutrient retention showed a general trend of decreasing, increasing, and then decreasing. Soil conservation capacity (Figure 2c) had high values that were relatively more common in the northeastern part of the city; low values were more widely distributed in the city, with no obvious areas of concentration. Habitat quality (Figure 2d) had high values that were mostly concentrated in the northeastern part of the city, with more areas of low values in the western and southern parts of the city. In the southwestern part of the city, the habitat quality declined significantly between 2000 and 2020, while in other areas it did not change significantly over time.

Overall, the differences in changes in each ecosystem service over time between 2000 and 2020 were not significant, and the values were relatively stable. However, the spatial pattern distribution of different ecosystem services varied greatly, and the spatial clustering characteristics of the values of different ecosystem services were more obvious. Water yield had low values in most areas of Guiyang City, but there was an area of high values in the western part of the city, where the Hongfeng Lake Scenic Spot is located, with a large area of natural watersheds giving this part of the city a high-water retention capacity. Nutrient retention and soil conservation capacity did not have a clear concentration of high values in Guiyang City; in particular, soil conservation capacity had low values in the vast majority of areas in the city, which was mainly due to the influence of the karst topography of Guiyang City, as the bedrock was mostly dissolvable carbonate rock, resulting in the region's infertile soils, thin soil layers, poor filtering of water, and serious soil erosion. Habitat quality was consistently lower in the regions of the main and old urban areas in the south of Guiyang City, which indicated that the construction and development of the city had caused significant habitat destruction, resulting in a decline in habitat quality. Admittedly, the distribution pattern of ecosystem services was also affected by many driving factors, so the way of combining these factors to delineate a more accurate and scientific regional range of high ecosystem service levels was the main focus of this threshold study.

3.2. Thresholds of Ecosystem Service Drivers

In the fitting model for the RCS analysis, all four ecosystem services and the 12 drivers satisfied a nonlinear relationship, and the R^2 value of the model was greater than 0.5, so it could explain the interactions between the variables and, therefore, identify certain thresholds of natural and social factors through changes in ecosystem services.

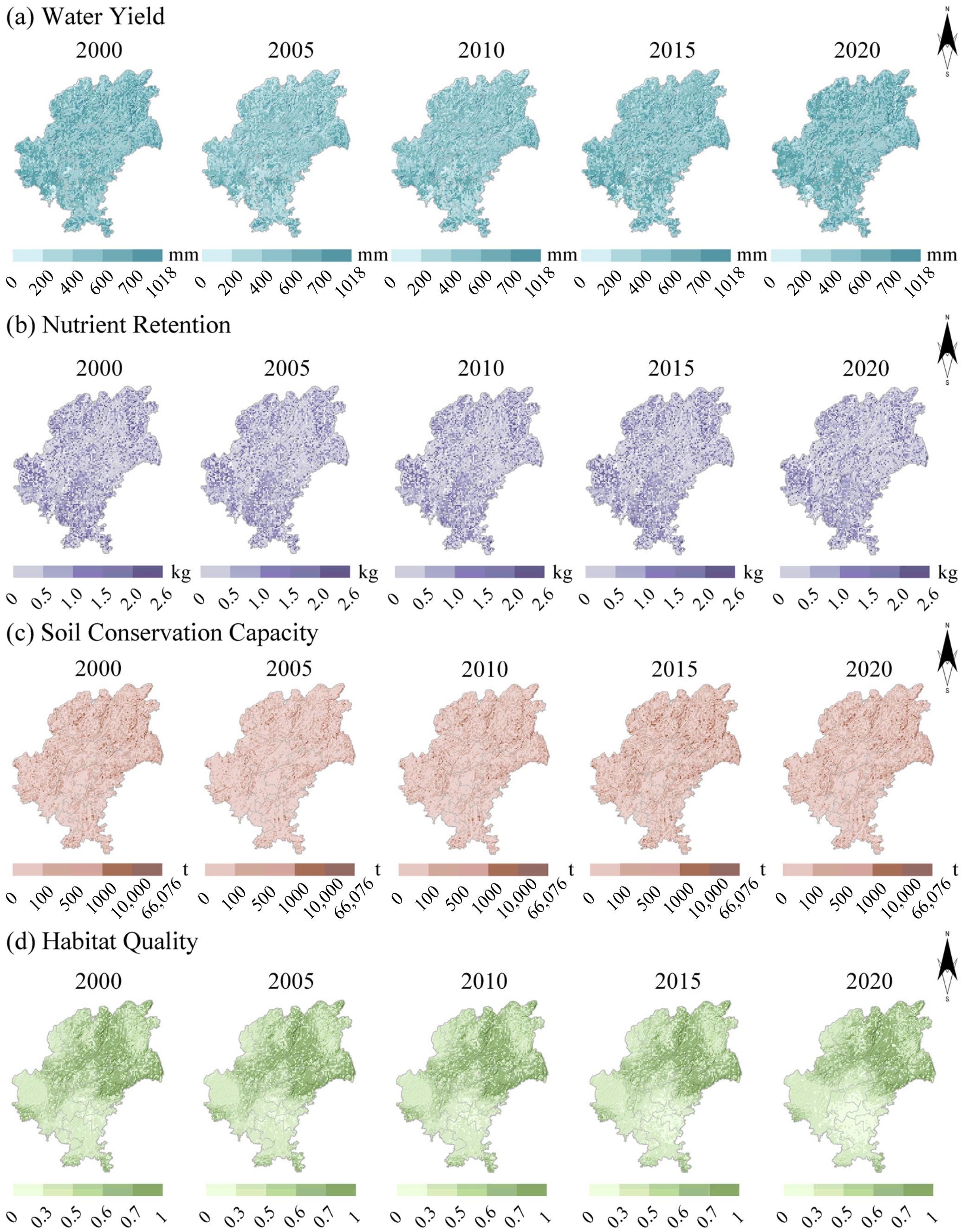


Figure 2. Patterns of spatial and temporal changes in (**a**) water yield, (**b**) nutrient retention, (**c**) soil conservation capacity, and (**d**) habitat quality in Guiyang City, China, from 2000 to 2020.

3.2.1. Drivers of the Thresholds of Water Yield

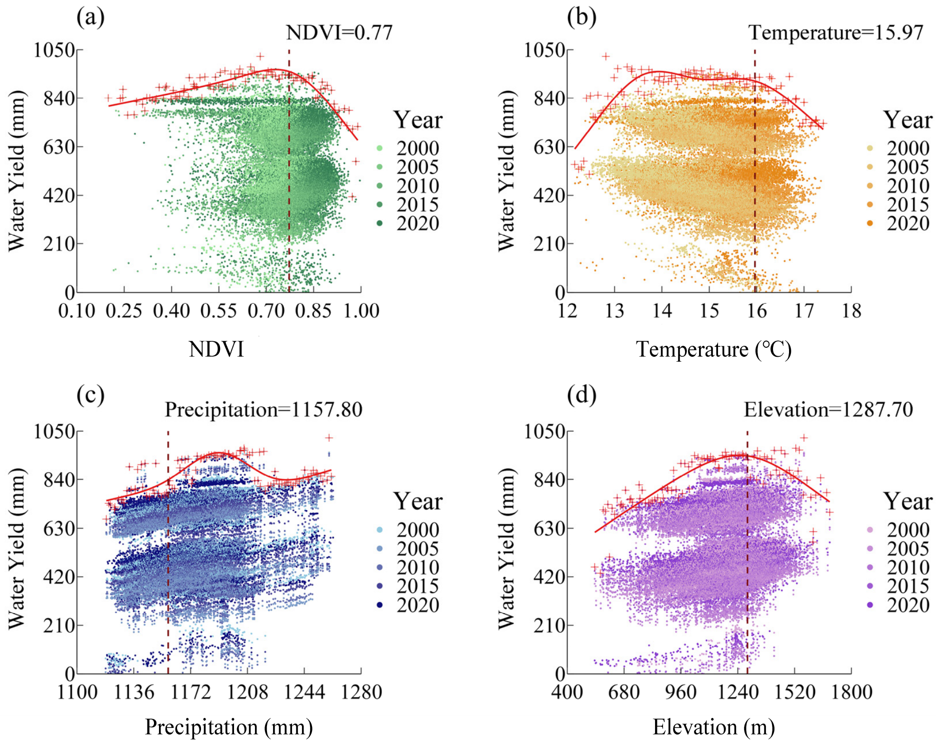
The effects of different natural factors on water yield varied considerably (Figure 3a–f). Water yield increased faster when the NDVI was less than 0.77, and then it showed a rapid decline (Figure 3a), which indicated that it was more sensitive to the effects of the NDVI and that high vegetation cover could help to increase the water yield, but overly dense vegetation would cause a decrease in it. The water yield was higher when the temperature was greater than 15.97 °C (Figure 3b) and the precipitation was greater than 1157.80 mm (Figure 3c), which indicated that higher temperatures and more precipitation had a positive effect on it. In addition, the water yield had a significant increasing trend with elevation, and it was at a high level after the elevation was greater than 1287.70 m (Figure 3d). When the slope was less than 43.64° (Figure 3e) and the relief amplitude was less than 331.60 m

(Figure 3f), the water yield could be maintained at a high level, which indicated that a moderate slope and relief amplitude were favorable for increasing the water yield.

The effect of social factors on the change In water yield were relatively weak (Figure 3g–l). The water yield was higher when the population density was greater than 252.03 person·km^{-2} (Figure 3g), indicating that a certain population density could increase it. The nighttime light intensity had a negative effect on the water yield, which was higher when the intensity was less than 23.47 nW·cm^{-2}·sr^{-1} (Figure 3h). The water yield was inversely related to all four distance factors, with excessive distance presenting a lower water yield. It was higher when the distance to road was less than 5.35 km (Figure 3i) and the distance to water was less than 8.42 km (Figure 3j), and it was higher when the distance to urban land (DTUL) was less than 32.81 km (Figure 3k) and the distance to rural settlement (DTRS) was less than 25.17 km (Figure 3l). To focus on a higher water yield, areas closer to the same proximity should be considered.

3.2.2. Drivers of the Thresholds of Nutrient Retention

Nutrient retention was differently affected by different natural factors (Figure 4a–f). An NDVI greater than 0.79 resulted in higher nutrient retention (Figure 4a), indicating that increased vegetation was more favorable for water purification. Nutrient retention was able to provide a higher level when the temperature was greater than 15.86 °C (Figure 4b), and higher temperature increased nutrient retention. Nutrient retention was higher when precipitation was less than 1223.07 mm (Figure 4c), indicating that suitable precipitation was more effective for water purification. Changes in elevation caused large fluctuations in nutrient retention, and when the elevation was less than 1376.48 m, it tended to increase significantly and then declined faster (Figure 4d). Lower elevation was favorable for controlling the higher level of water purification. When the slope was less than 44.92° (Figure 4e) and the relief amplitude was less than 147.05 m (Figure 4f), the nutrient retention was higher and then decreased rapidly, indicating that areas with a lower slope and relief amplitude were areas of concern for high water purification levels. Water purification services responded more sensitively to changes in slope and relief amplitude.



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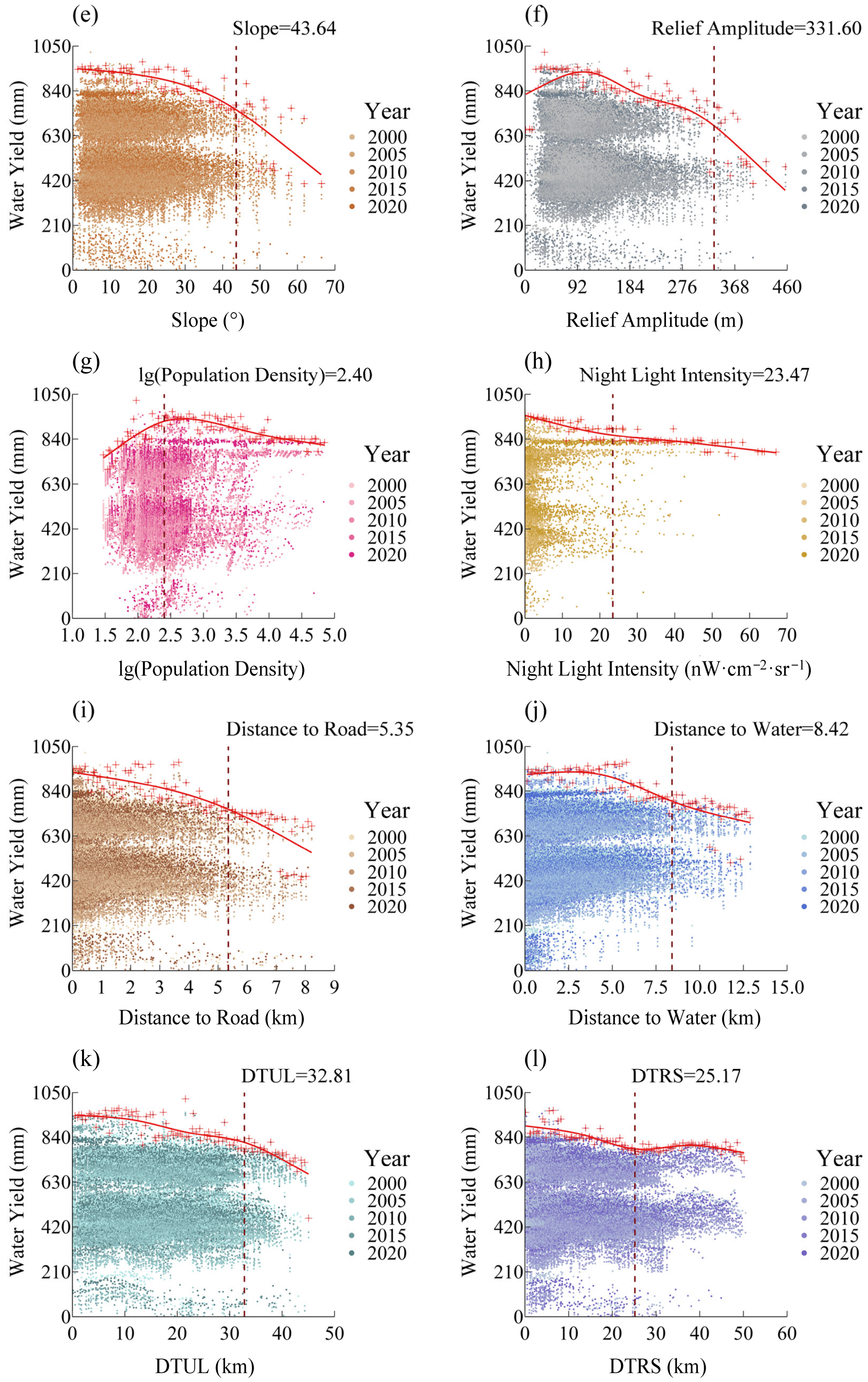
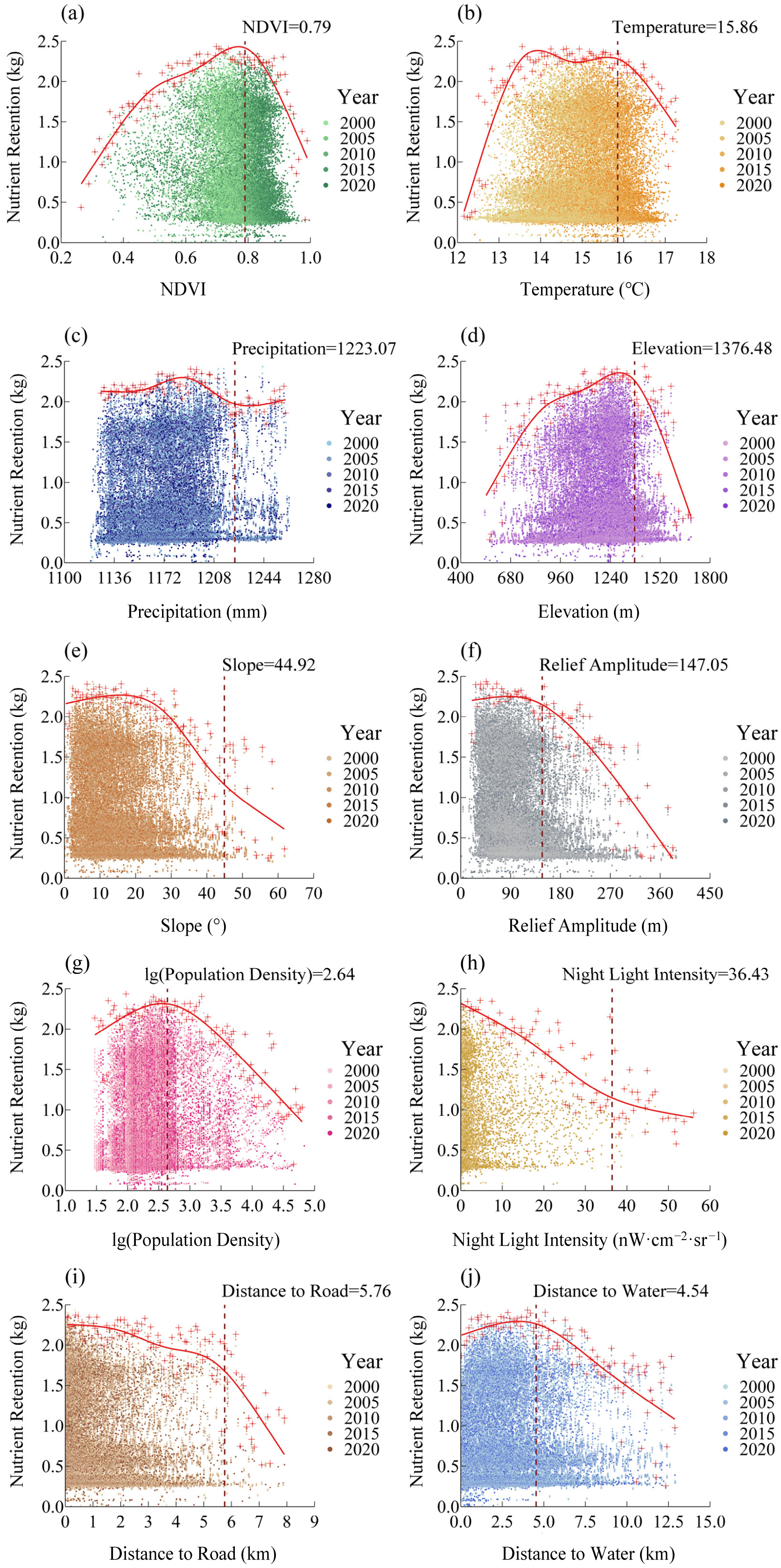


Figure 3. Relationships between water yield and natural drivers ((**a**) NDVI, (**b**) temperature, (**c**) precipitation, (**d**) elevation, (**e**) slope, and (**f**) relief amplitude) and social drivers ((**g**) population density, (**h**) nighttime light intensity, (**i**) distance to road, (**j**) distance to water, (**k**) DTUL, and (**l**) DTRS) in Guiyang City, China. Notes: The colored dots indicate the scattering cloud between different ecosystem services and drivers; the red crosses indicate the selected 99.9% quantile boundary points; the red solid lines indicate the constraint lines constructed based on the boundary points; and the red dashed lines indicate the corresponding positions of the x-axis delineated by the key turning nodes identified based on the constraint lines.



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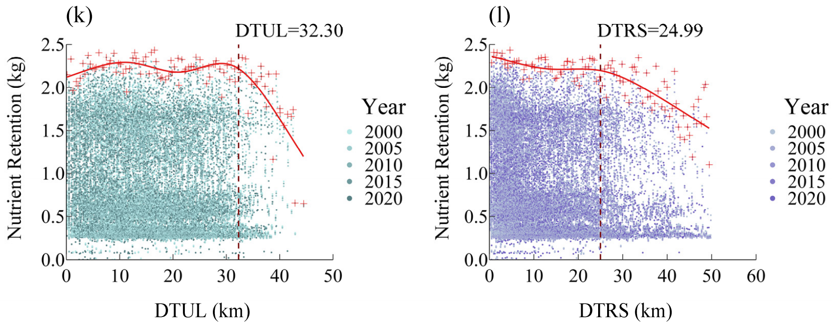

Figure 4. Relationships between nutrient retention and natural drivers ((**a**) NDVI, (**b**) temperature, (**c**) precipitation, (**d**) elevation, (**e**) slope, and (**f**) relief amplitude) and social drivers ((**g**) population density, (**h**) nighttime light intensity, (**i**) distance to road, (**j**) distance to water, (**k**) DTUL, and (**l**) DTRS) in Guiyang City, China. Notes: The colored dots indicate the scattering cloud between different ecosystem services and drivers; the red crosses indicate the selected 99.9% quantile boundary points; the red solid lines indicate the constraint lines constructed based on the boundary points; and the red dashed lines indicate the corresponding positions of the *x*-axis delineated by the key turning nodes identified based on the constraint lines.

The differences in the effects of different social factors on nutrient retention were relatively significant (Figure 4g–l). Nutrient retention was higher when the population density was less than 435.11 person·km^{-2} and then decreased rapidly (Figure 4g), indicating that water purification services were more sensitive to population density, and smaller population densities were more appropriate. Nutrient retention was relatively high when the nighttime light intensity was less than 36.43 nW·cm^{-2}·sr^{-1}, and then it remained at a relatively low level (Figure 4h). Regarding the distance factor, nutrient retention should be considered in closer areas, and water purification services were maintained at high levels when the distance to road was less than 5.76 km (Figure 4i), the distance to water was less than 4.54 km (Figure 4j), the distance to urban land (DTUL) was less than 32.30 km (Figure 4k), and distance to rural settlement (DTRS) was less than 24.99 km (Figure 4l).

3.2.3. Drivers of the Thresholds of Soil Conservation Capacity

Soil conservation capacity responded differently to changes in different natural factors (Figure 5a–f). Soil conservation capacity was higher when the NDVI was greater than 0.80 (Figure 5a), suggesting that high vegetation cover was likewise beneficial in increasing its level. Soil conservation capacity showed an increasing trend when the temperature was less than 15.59 °C (Figure 5b) and precipitation was less than 1190.10 mm (Figure 5c), after which it decreased significantly, indicating that a relatively mild climate was helpful in increasing the level of soil conservation capacity. Soil conservation capacity showed an increase and then a decrease with elevation, and it gradually increased when the elevation was less than 1282.95 m (Figure 5d). However, the threshold was relatively insignificant, and the elevation could be excluded as a key concern. When the slope was less than 45.03° (Figure 5e) and the relief amplitude was less than 233.00 m (Figure 5f), the soil conservation capacity could be maintained at a certain higher value.

Soil conservation capacity varied relatively little as a result of social factors and was relatively insensitive to their responses (Figure 5g–l). Population density had a negative effect on the soil conservation capacity, which was higher when the population density was less than 1426.35 person·km^{-2} (Figure 5g). Soil conservation capacity was higher with a nighttime light intensity of less than 43.58 nW·cm^{-2}·sr^{-1}, and then it remained at lower values (Figure 5h). Soil conservation services should focus on areas with less nighttime light intensity. Soil conservation capacity varied less with the distance factor; when the distance to road was less than 5.27 km (Figure 5i), the distance to water was less than 8.40 km (Figure 5j), and the distance to urban land (DTUL) was less than 31.68 km (Figure 5k), it kept a high value. When the distance to rural settlement (DTRS) was less than 32.79 km (Figure 5l), it remained relatively high, and then it had a lower level, but the threshold was not significant, so it can be excluded as a factor to be emphasized when studying soil conservation services.

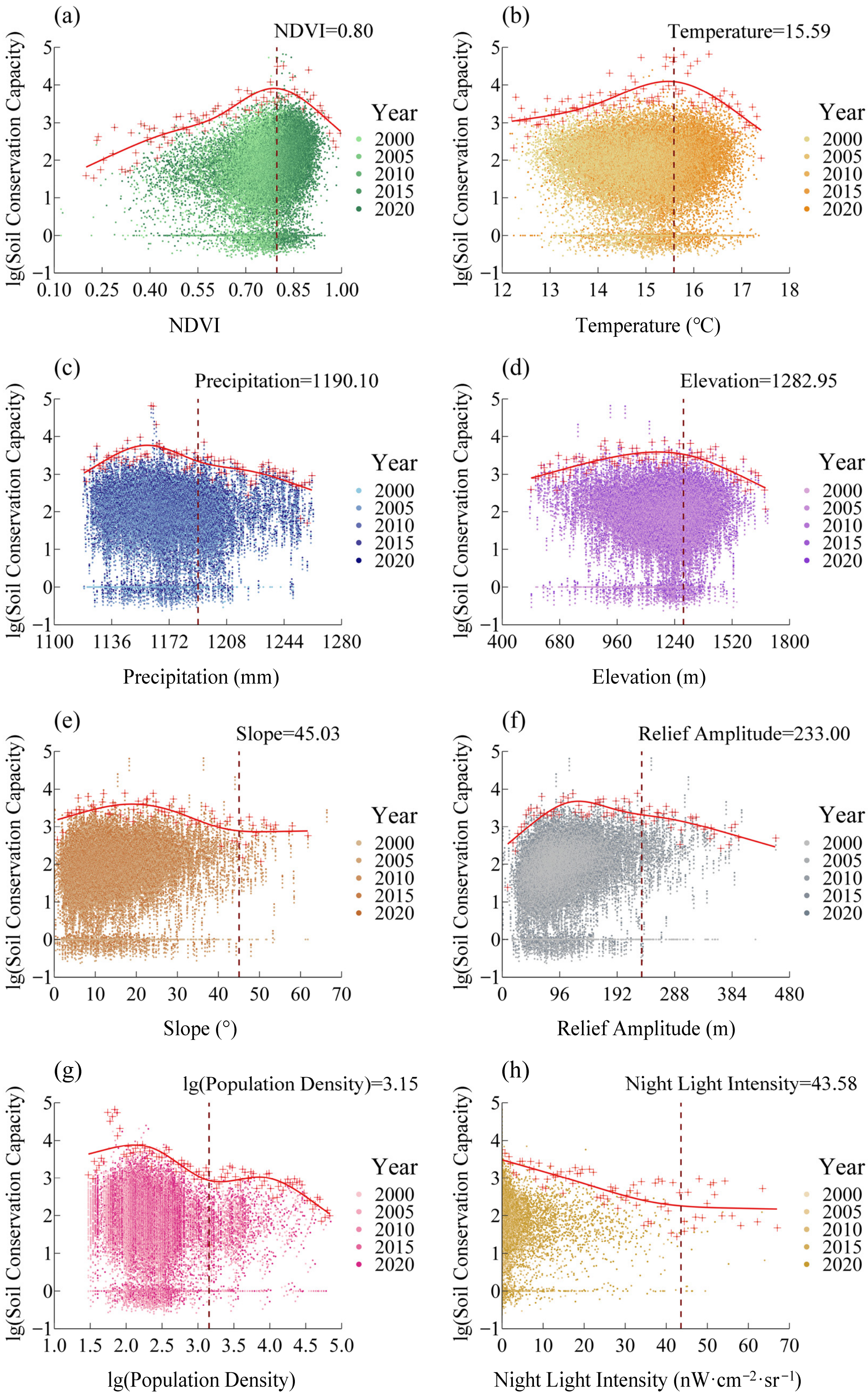

Figure 5. *Cont.*

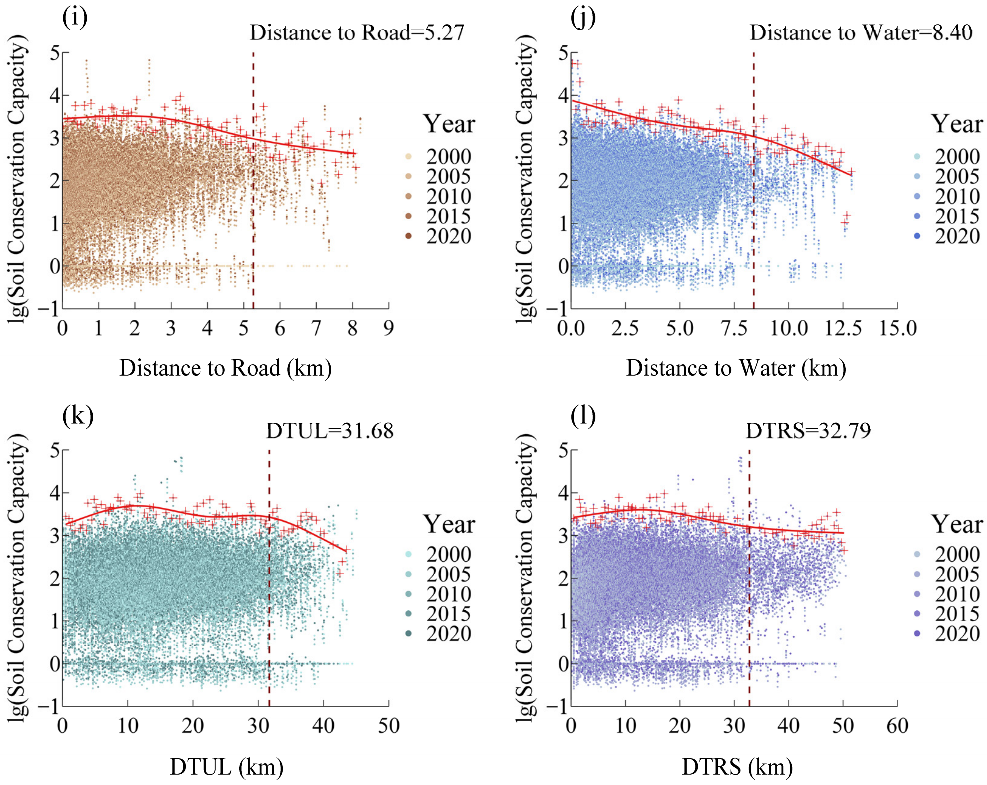

Figure 5. Relationships between soil conservation capacity and natural drivers ((**a**) NDVI, (**b**) temperature, (**c**) precipitation, (**d**) elevation, (**e**) slope, and (**f**) relief amplitude) and social drivers ((**g**) population density, (**h**) nighttime light intensity, (**i**) distance to road, (**j**) distance to water, (**k**) DTUL, and (**l**) DTRS) in Guiyang City, China. Notes: The colored dots indicate the scattering cloud between different ecosystem services and drivers; the red crosses indicate the selected 99.9% quantile boundary points; the red solid lines indicate the constraint lines constructed based on the boundary points; and the red dashed lines indicate the corresponding positions of the x-axis delineated by the key turning nodes identified based on the constraint lines.

3.2.4. Drivers of the Thresholds of Habitat Quality

Habitat quality varied greatly with natural factors (Figure 6a–f). Habitat quality was elevated with the increase in the NDVI, and it was higher when the NDVI was greater than 0.82 (Figure 6a), indicating that areas with higher vegetation cover had higher habitat quality. Habitat quality was higher when the temperature was less than 15.92 °C (Figure 6b) and precipitation was less than 1191.46 mm (Figure 6c), after which it began to decrease, and suitable temperature and moderate precipitation were helpful in improving it. Habitat quality could be maintained at a high level when the elevation was higher than 1375.93 m (Figure 6d), indicating that it was higher in higher-elevation areas. When the slope was less than 44.84° (Figure 6e) and the relief amplitude was less than 332.70 m (Figure 6f), the habitat quality was maintained at a high value, and a smaller slope and relief amplitude were able to maintain a high habitat quality.

The response of habitat quality to different social factors also varied (Figure 6g–l). Habitat quality was higher when the population density was less than 1426.35 person·km^{-2}, and then it decreased rapidly (Figure 6g), which indicated that it was more sensitive to changes in population density. Habitat quality was relatively high when the nighttime light intensity was less than 29.17 nW·cm^{-2}·sr^{-1}, and then it was maintained at a low level (Figure 6h); thus, it was likewise more sensitive to the nighttime light intensity. Regarding distance factors, the habitat quality was higher when the distance to road was less than 2.91 km (Figure 6i), the distance to water was less than 8.39 km (Figure 6j), and the distance to urban land (DTUL) was less than 32.80 km (Figure 6k). Priority should be given to areas closer to these influences. The habitat quality decreased with the increase in distance to rural settlement (DTRS) and then recovered (Figure 6l); when the distance was less than 36.75 km, the habitat quality was higher, but the thresholds were not sensitive, and priority should be given to areas influenced by other factors.

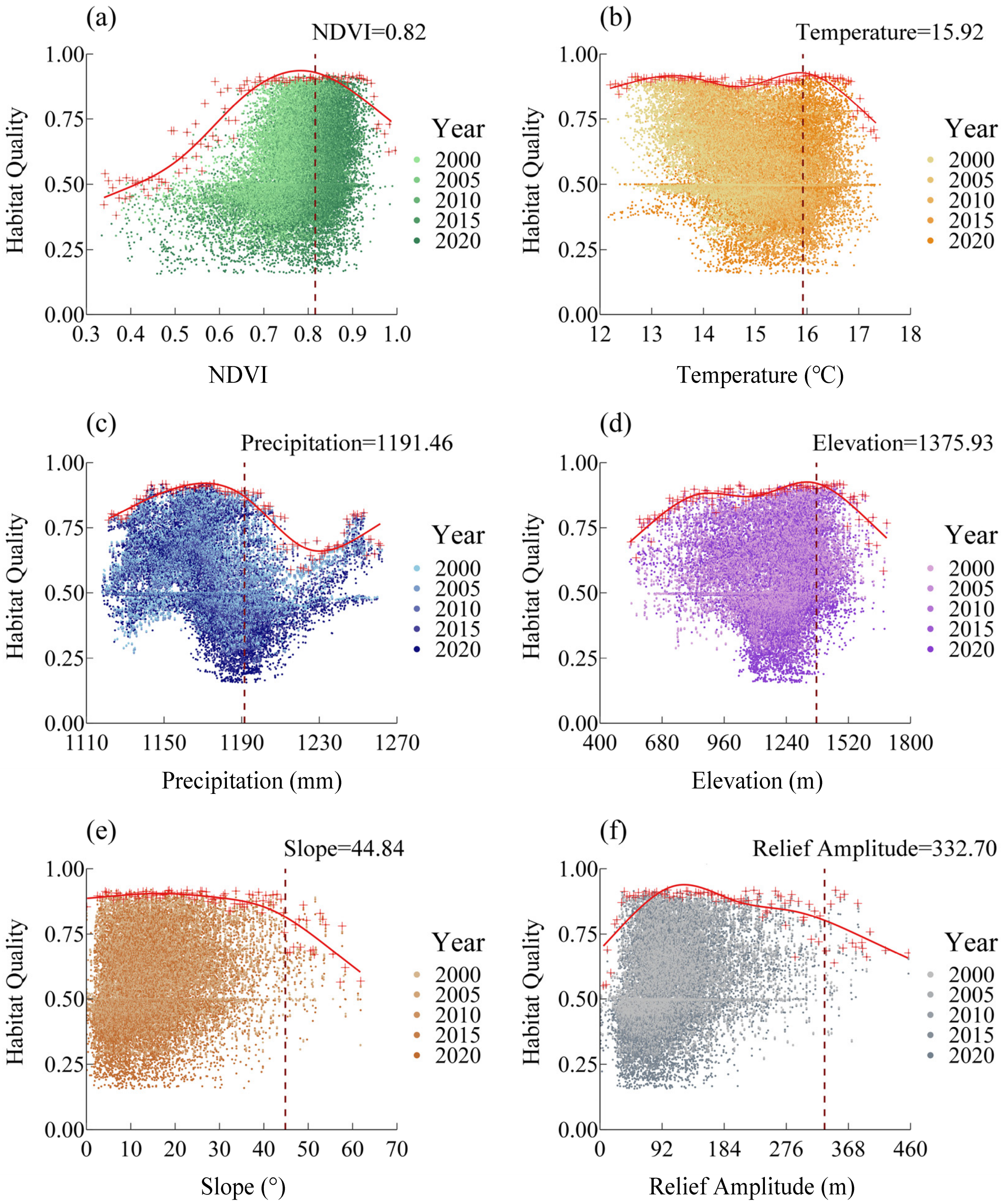

Figure 6. *Cont.*

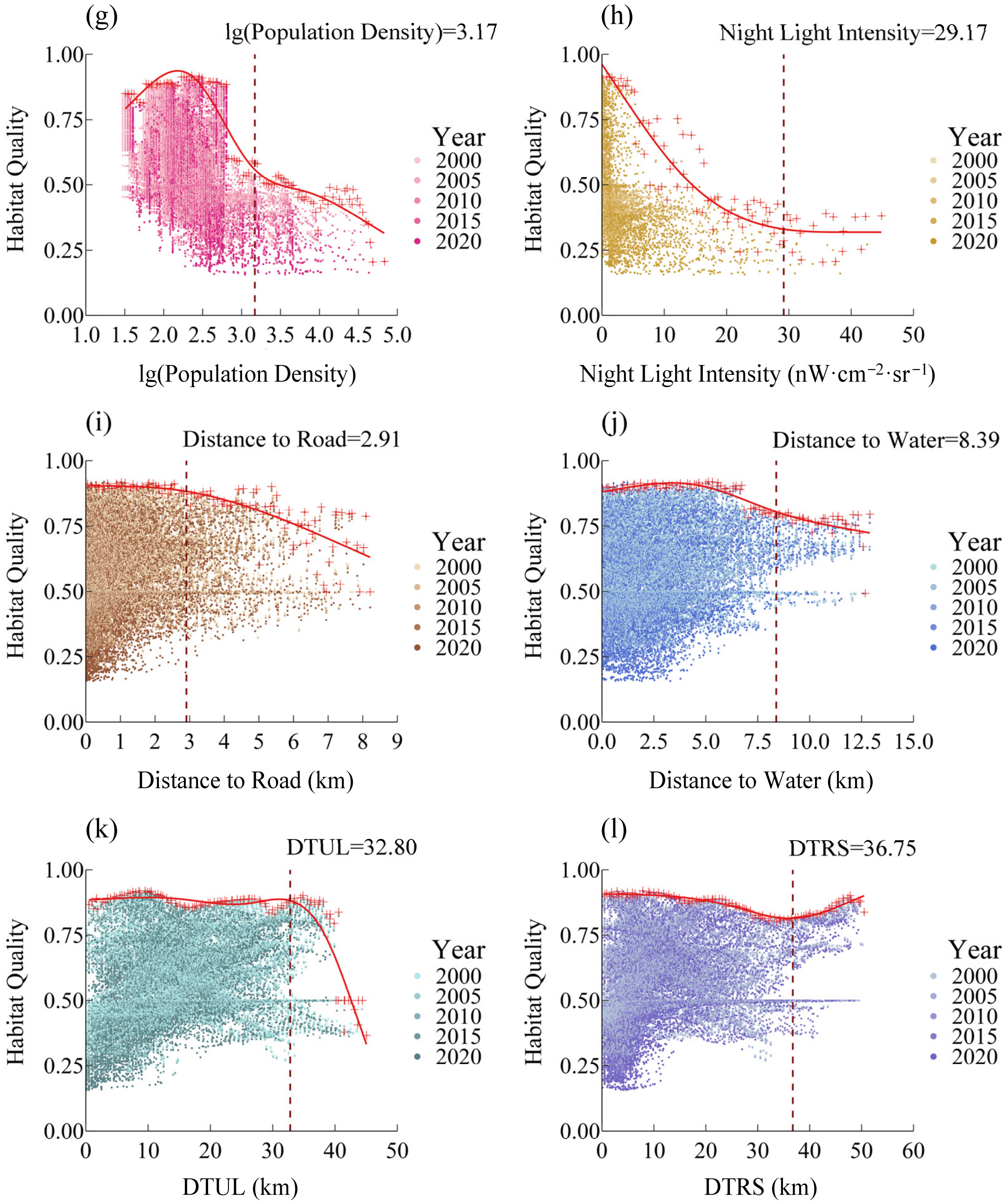

Figure 6. Relationships between habitat quality and natural drivers ((**a**) NDVI, (**b**) temperature, (**c**) precipitation, (**d**) elevation, (**e**) slope, and (**f**) relief amplitude) and social drivers ((**g**) population density, (**h**) nighttime light intensity, (**i**) distance to road, (**j**) distance to water, (**k**) DTUL, and (**l**) DTRS) in Guiyang City, China. Notes: The colored dots indicate the scattering cloud between different ecosystem services and drivers; the red crosses indicate the selected 99.9% quantile boundary points; the red solid lines indicate the constraint lines constructed based on the boundary points; and the red dashed lines indicate the corresponding positions of the *x*-axis delineated by the key turning nodes identified based on the constraint lines.

3.3. Natural and Social Thresholds of Different Ecosystem Services

Based on the nonlinear relationships presented by the constraint lines, the key natural and social thresholds of concern for four karst ecosystem services were identified and determined (Table 2). The key natural thresholds for the water supply (water yield) included slope (≤43.64°) and relief amplitude (≤331.60 m), and the key social thresholds included distance to road (≤5.35 km) and distance to water (≤8.42 km). The key natural thresholds for water purification (nutrient retention) included slope (≤44.92°) and relief amplitude (≤147.05 m), and the key social thresholds included distance to a water (≤4.54 km), distance to urban land (DTUL) (≤32.30 km), and distance to rural settlement (DTRS) (≤24.99 km). The key natural thresholds for soil conservation (soil conservation capacity) included normalized difference vegetation index (NDVI) (≥0.80) and relief amplitude (≤233.00 m), and the key social thresholds included population density (≤1246.35 person·km^{-2}), nighttime light intensity (≤43.58 nW·cm^{-2}·sr^{-1}), and distance to water (≤8.40 km). The key natural thresholds for biodiversity maintenance (habitat quality) included normalized difference vegetation index (NDVI) (≥0.82), precipitation (≤1191.46 mm), and slope (≤44.84°), and the key social thresholds included population density (≤1481.06 person·km^{-2}), nighttime light intensity (≤29.17 nW·cm^{-2}·sr^{-1}), and distance to urban land (DTUL) (≤32.80 km). For different ecosystem services, depending on their degree of influence by natural or social factors, the key thresholds of the corresponding factors can be focused on to meet the corresponding research needs.

Table 2. Natural and social thresholds for higher levels of different ecosystem services.

Thresholds	Drivers	Water Yield	Nutrient Retention	Soil Conservation Capacity	Habitat Quality
Natural driving factor threshold	Normalized difference vegetation index (NDVI)	≤0.77	≥0.79	≥0.80	≥0.82
	Temperature (°C)	≥15.97	≥15.86	≤15.59	≤15.92
	Precipitation (mm)	≥1157.80	≤1223.07	≤1190.10	≤1191.46
	Elevation (m)	≥1287.70	≤1376.48	-	≥1375.93
	Slope (°)	≤43.64	≤44.92	≤45.03	≤44.84
	Relief amplitude (m)	≤331.60	≤147.05	≤233.00	≤332.70
Social driving factor threshold	Population density (person·km^{-2})	≥252.03	≤435.11	≤1426.35	≤1481.06
	Night light intensity (nW·cm^{-2}·sr^{-1})	≤23.47	≤36.43	≤43.58	≤29.17
	Distance to road (km)	≤5.35	≤5.76	≤5.27	≤2.91
	Distance to water (km)	≤8.42	≤4.54	≤8.40	≤8.39
	Distance to urban land (DTUL) (km)	≤32.81	≤32.30	≤31.68	≤32.80
	Distance to rural settlement (DTRS) (km)	≤25.17	≤24.99	-	-

4. Discussion

4.1. Threshold Effects between Different Ecosystem Services and Different Drivers

Defining how environmental factors affect ecosystem services, identifying thresholds for natural and social factors, and controlling the range of influencing factors to maintain a high level of ecosystem services in a region can meet the needs of environmental policy makers and managers for ecological planning. For example, by investing in the restoration of a watershed's capacity to filter water, additional services, including carbon capture and flood prevention, as well as recreational and cultural benefits, were provided at no extra cost [80]; ecosystem service-based soil functions can establish a categorization that supports spatial planning policies and regulations and land valuation [81].

A study on the Beijing–Tianjin–Hebei urban agglomeration in China analyzed the nonlinear relationship between the total ecosystem service value and its drivers, and critical thresholds were identified [82]. The main natural and anthropogenic thresholds included elevation (687 m), slope (13.4°), NDVI (0.7), and distance to road (1.1 km). A study on the peri-urban areas of Beijing in China analyzed the response of ecosystem services to urbanization in a metropolitan area [83]. It was found that the response of the total amount of ecosystem services (TES) to population density had a threshold value

(229 person·km^{-2}), and when the population density reached the threshold value, the TES significantly decreased with population growth. Compared with the results of previous threshold studies that selected non-karst regions, the elevation threshold in this study was relatively high, averaging around 1300 m, due to the higher average elevation of the study area compared to the Beijing–Tianjin–Hebei region of China. Because the regional landscape of Guiyang City is dominated by mountainous hills, while the Beijing–Tianjin–Hebei region is dominated by plains, the slope threshold is also relatively high, averaging around 44.6°. At the same time, because the urbanization of the Beijing–Tianjin–Hebei region is more rapid than that of the karst region where Guiyang City is located and the economic development is relatively better, the population density and road network density are denser than those of Guiyang City. Due to the regional scope of Guiyang City, where the impacts of human activities are smaller and the thresholds of the drivers are higher, the threshold for population density was around 900 person·km^{-2} on average, and the threshold for the distance to road was around 5 km on average; the other thresholds were also higher than those in the Beijing–Tianjin–Hebei region. At the same time, a study on Fujian Province in China identified the dominant factors influencing ecosystem service relationships [84]. In the study, 17 potential influencing factors were comprehensively screened from five aspects of human activities, land use types, climate, topography, and habitat characteristics. Among them, annual total precipitation, annual sunshine radiation, annual average temperature, distance from railway, and GDP density were the dominant factors affecting ecosystem service relationships. The findings of climatic factors are consistent with our study that there are thresholds for both temperature and precipitation responses to ecosystem services. As for distance factors, due to the low density of railroads within the Guiyang City area, we selected additional distance factors as representative indicators, including distance to road, distance to water, distance to urban land, and distance to rural settlement, which had also been proven to have certain thresholds in our study. And as nighttime light (NTL) can be used as a proxy for economic activity [85], the nighttime light intensity indicator of our study can be corresponded to the GDP density, there are also thresholds. In addition, a study on the Hunshandak sandy land in the dryland region of China found driving factors have inflection points and thresholds for the impact of ecosystem services relationships [86]. Temperatures ranging from 2.8 to 3 °C and precipitation ranging from 300 to 400 mm are most conducive to coordinated development among ecosystem services in the dryland. Compared with the arid plains, the karstic mountains have a wetter climate and more precipitation overall, while the region's vegetation is richer and more diverse, with a higher carrying capacity for high temperatures, resulting in relatively higher temperature and precipitation thresholds in Guiyang City.

Comparisons showed that natural and social thresholds were generally higher in karst regions than in non-karst regions [87], suggesting that in karst regions, where there is relatively less human intervention, more diverse landscapes, and more bioecological richness, the ecosystems have a better capacity to accommodate a wider range of thresholds that can provide more ecosystem services [88]. Although karst environments result in fragile and fragmented natural landscapes, they create unique karst landscapes, such as sinkholes and caves, which are preserved in a more pristine state and provide a richer variety of organisms and a more diverse range of habitats, resulting in a greater and a wider range of natural thresholds for karst ecosystem services than those in non-karst areas, where space for natural environments is constricted by socioeconomic development. At the same time, due to the obvious environmental constraints in karst regions that can be used by human beings to promote social development, the urbanization of such regions has been slowed to a certain extent; thus, the social thresholds of karst ecosystem services are more sensitive, and the differences in the social thresholds of different ecosystem services are more prominent.

The results of this study show that different ecosystem services correspond to different driver thresholds, and the response of the same driver to different ecosystem services varies.

Four social factors, namely, population density, nighttime light intensity, distance to road, and distance to water, were the most influential on different ecosystem services and had more pronounced differences in thresholds than those of natural factors. Therefore, it is necessary to consider different natural and social thresholds for different ecosystem services when focusing on these factors. The thresholds for the other factors were less affected by different ecosystem services, and it is possible to consider combining the thresholds in planning to reduce implementation and management costs [89]. Existing research on ecosystem service thresholds combine multiple ecosystems to explore thresholds for overall ecosystem services, with only one threshold range being derived for each driver. In contrast, our study demonstrated that it is necessary to delineate different thresholds for different types of ecosystem services when there is a need to focus on specific drivers.

4.2. Implications and Future Directions

Existing studies on the analysis of drivers of karst ecosystem services explored them using the GeoDetector model [90], which showed that the slope [91], precipitation [27], vegetation cover [92], and population density [28] are the main drivers affecting ecosystem services in karst areas, and these factors are consistent with the findings in this study, which analyzed threshold effects to find the key factors. However, at the same time, drivers that were considered non-critical in previous studies, such as temperature [93], were still able to contribute quite positively to the improvement of ecosystem services by identifying and delineating the threshold ranges of such factors, as evidenced by the results of this study. In addition, this study also provides some noteworthy new drivers for the study of ecosystem services in karst regions based on the key thresholds. The results of this study provide a new idea for the exploration of the key drivers of karst ecosystem services, improving the level of ecosystem services in karst areas, and improving the sustainable management of regional landscape ecology.

As ecosystem services are interconnected in complex and dynamic ways, geospatial variations in ecosystem services are induced by different policies in different regions [94], so different ecosystems in different regions should be given different emphases where appropriate. Conservation planners have called for the inclusion of ecosystem services in the assessment of priority areas for ecological conservation, including biodiversity patterns. A focus on 'special' habitats in a conservation assessment ensures that the services that they provide, such as carbon sequestration and water regulation, continue to be delivered. Considering ecological processes, support for the persistence of biodiversity patterns, such as pollination, climate change resilience, nutrient cycling, primary productivity, and sediment transport, can be used to form links to ecosystem services. Regarding the mapping of ecosystem services, areas of ecosystem service supply and areas of demand can be mapped in an effort to evaluate and manage the benefit flows of these services [95]. In addition, ecological restoration projects should ensure that multiple ecosystem functions meet the needs of different stakeholders [96]. Thus, for the results derived in this study, the ways in which the thresholds of natural and social drivers with high ecosystem service levels can be further applied to ecological conservation planning in different regions need to be further explored.

5. Conclusions

This study quantified four ecosystem services in Guiyang City; we explored and identified the thresholds between ecosystem services and drivers by analyzing the nonlinear relationships between different ecosystem services and different natural and social drivers. The results showed that there were certain threshold effects between karst ecosystem services and their natural and social drivers, and the thresholds of the drivers had different response sensitivities for different ecosystem services. For four ecosystem services, natural thresholds were more pronounced than social thresholds. This study explored the identification of natural and social thresholds for the maintenance of high levels of ecosystem services in a karst region from a unique perspective, and different ranges of thresholds were identified for different ecosystem services. For government departments or researchers who focus on different ecosystem services, it is possible to prioritize areas according to the corresponding natural and social thresholds, which will facilitate subsequent ecological planning and other studies.

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